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Dissipation and Dynamical Friction Effects on the Number of Star Clusters in a Galaxy

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Abstract—The evolution of the number of globular clusters in a galaxy of arbitrary mass and constant circular velocity is investigated. Numerical simulations have led to the following principal conclusions: (a) if the initial number of clusters is proportional to the mass of the parent galaxy, the current specific frequency of clusters (S_N) must be higher in more massive galaxies; (b) S_N abruptly decreases with age for low-mass galaxies and can be virtually equal to zero in galaxies with $M_g < 10^9 M_\odot$; (c) reconstruction of the initial cluster population suggests that the initial specific frequency of clusters was the same in different galaxies.

INTRODUCTION

Globular clusters are the witnesses of galaxy formation. Not only their physical parameters but also the number of clusters in a galaxy bear information about the formation process of the stellar system. The number of globular clusters per unit mass of the galaxy is an especially important parameter. The same value of this parameter for different galaxies would suggest pregalactic origin of globular clusters. However, in contrast to the mass of the galaxy, the number of globular clusters in it does not remain constant: star clusters form and disrupt in the course of galactic evolution and these effects are to be allowed for when comparing theory with observations.

In this paper, we estimate the effect of the two strongest and the most systematically acting processes on the number of globular clusters in a galaxy. We ignore possible formation of globular clusters during epochs other than the epoch of galaxy formation: according to observations, globular cluster systems in most of galaxies are populated by coeval cluster samples of close to cosmological age. Of various effects leading to disruption of globular clusters we analyze only the two most important ones: dissipation due to star-star relaxation and dynamical friction which makes the cluster fall onto the central part of the galaxy (Surdin 1978; Spitzer 1987; Surdin 1993).

DYNAMIC EVOLUTION EFFECTS

Here, we analyze dynamic effects in the galaxies of various types and therefore adopt a general mass distribution model in the form of singular isothermal sphere defined by a single parameter -circular velocity V_c which remains constant throughout the entire range of galactocentric radii R. This model has a density distribution in the form $\rho \propto R^{-2}$ and a more simple mass distribution:

$$M_g(R) = \frac{RV_c^2}{G}. \quad (1)$$

We now consider *dynamical friction*, which slows down the motion of massive star clusters moving through a medium of low-mass field stars (Binney and Tremain 1987). Dynamical friction does not result in direct destruction of the cluster. This effect, however, causes the radii of the cluster orbit in the galaxy to decrease and the cluster to enter the central region of the galaxy where it is dissolved by tidal fields. The frictional force on the cluster moving in a steady-state nonrotating galaxy is equal to:

$$M\frac{d\mathbf{v}}{dt} = -4\pi G^2 M^2 \frac{\mathbf{v}}{v^3} \ln\frac{d_{\max}}{d_{\min}} \int_0^v \rho(v')dv', \quad (2)$$

where G is the gravitational constant, M and $\mathbf{v}$ are the cluster mass and velocity, respectively; $\rho(v')dv'$ is the three-dimensional mass density of field stars with velocities in the $[v', v' + dv']$ interval; $d_{\max}$ and $d_{\min}$ are the maximum and minimum impact factors for field stars with respect to the cluster center, respectively. For a globular cluster in a typical galaxy the Coulomb logarithm in eq. (2) is equal to 7. For Maxwellian velocity distribution the integral in the right-hand side of eq. (2) is equal to $0.428\rho v$. Adopting the above values we infer from formula (2) for a quasicircular cluster orbit the radius decrease rate due to dynamical friction in a nonrotating isothermal sphere is:

$$\frac{dR}{dt} = -\frac{3GM}{V_c R}. \quad (3)$$

As a result, the cluster initially located at a galactocentric distance R and moving in a spiral trajectory

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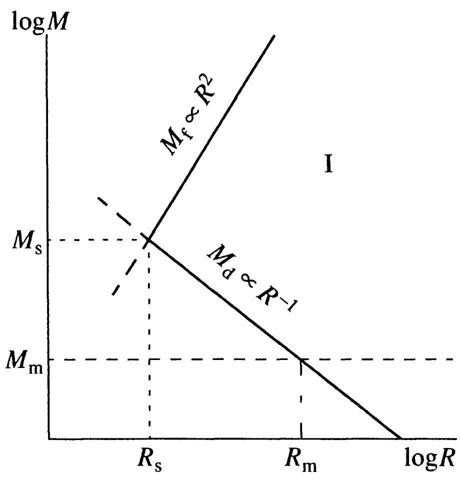

Fig. 1. Solid line in the "mass-radius of orbit" plane shows the boundaries of the domain of slow evolution (I) of globular clusters. M_s and R_s determine the location of the survival cone summit and increase with the age of the galaxy. The lower boundary, M_m, is equal either to the minimum cluster mass in the initial distribution (M_t) or to the limiting observed mass, M_{lim}.

reaches the center of the galaxy after time:

$$t_f = \frac{V_c R^2}{6GM}. \tag{4}$$

Quadratic dependence of t_f on R results in a protracted evolution of the cluster near the initial R followed by accelerated motion toward the center of the galaxy. Therefore eq. (4) allows us to estimate the maximum mass (M_f) for the clusters whose orbits remain virtually unaffected by dynamical friction as a function of, t, and initial radius, R, of the orbit:

$$M_f = \frac{V_c}{6Gt}R^2. \tag{5}$$

If all clusters formed simultaneously during the cosmological epoch then only those with masses $M < M_f$ ($t = H_0^{-1}$, R) could have survived until the present day epoch.

Dissipation due to escape of stars from the cluster decreases the mass of the latter (Spitzer 1987) and results in complete cluster evaporation after time (Surdin 1994):

$$t_{ev} = \frac{1}{m}\left(\frac{Mr_h^3}{G}\right)^{1/2}, \tag{6}$$

where r_h is the half-mass radius of the cluster and m, the average mass of a cluster star. Here, we assume the latter to be equal to $0.3M_\odot$. The mass of a homologically evaporating cluster (with conservation of energy) depends on time as:

$$M = M_0\left(1 - \frac{t}{t_{ev}}\right)^{2/7}, \tag{7}$$

i.e., the mass starts changing rapidly only "on the eve" of the complete evaporation of the cluster. In view of this we can infer from (6) the effective minimum mass M_d for the clusters that remain virtually unaffected by dissipation after time t:

$$M_d = \frac{0.1Gt^2M_\odot^2}{r_h^3}. \tag{8}$$

The fact that r_h is related to the tidal radius $r_t = R(M/3M_g)^{1/3}$ of the cluster via King's concentration parameter $r_h \approx 0.7r_t \times 10^{-C/2}$ (Surdin 1994) allows us to eliminate the cluster radius from eq. (8):

$$M_d = \frac{M_\odot V_c t}{R} \times 10^{3C/4}. \tag{9}$$

Only clusters with masses $M > M_d(t, R, C)$ could have survived at a galactocentric distance R after time t. So far we are unable to determine structural parameters for globular clusters in the galaxies beyond the Local group and therefore we now simplify formula (9) by adopting for all clusters the same concentration parameter $C = 1.5$ based on the cluster data for our own Galaxy:

$$M_d = \frac{13M_\odot t V_c}{R}. \tag{10}$$

Only globular clusters with masses $M > M_d$ ($t = H_0^{-1}$, R) could have survived at a galactocentric distance R after cosmological time.

Equations (5) and (10) define on the $\{R, M\}$ plane a "survival cone" (see Fig. 1): a domain of conventionally acceptable (i.e., slowly evolving) cluster masses and orbital radii at time t in a galaxy with a circular velocity of V_c. The probability of finding a cluster beyond the survival cone is very low.

Joint solution of equations (5) and (10) yields R_s and M_s, the coordinates of the survival cone summit:

$$R_s = 0.33\left(\frac{t}{10^{10}\ \mathrm{yr}}\right)^{2/3}\ \mathrm{kpc} \tag{11}$$

and

$$M_s = 4 \times 10^4\left(\frac{V_c}{100\mathrm{km\ s^{-1}}}\right)\left(\frac{t}{10^{10}\ \mathrm{yr}}\right)^{1/3}M_\odot. \tag{12}$$

Interestingly, in the model that we adopted here R_s is independent of V_c, i.e., of the properties of the parent galaxy. $R_s \approx 0.5$ kpc for all galaxies at the present epoch. With time the survival cone drifts toward the peripheral regions of the galaxy.

REDUCTION OF GLOBULAR CLUSTER POPULATION

The initial number of clusters in a galaxy of radius R_g can be estimated by adopting an initial distribution of clusters on the orbital radius-mass plane, $W(M, R)$, and integrating this distribution over the entire R–M plane:

$$N_0 = \int_{\{R\}} \int_{\{M\}} W(M, R) 4\pi R^2 dR dM_\odot. \quad (13)$$

We can also determine the current number of the remaining clusters in the survival cone:

$$N = \int_{R_s}^{R_g} \int_{M_d}^{M_f} W(M, R) 4\pi R^2 dR dM. \quad (14)$$

When testing the hypotheses about pregalactic origin of globular clusters (Peebles and Dickey 1968; Peebles 1984; Rosenblatt *et al.* 1988) we must assume that the initial mass distribution of globular clusters was independent of the spatial distribution of clusters:

$$W(M, R) \propto f(M)\psi(R). \quad (15)$$

We can now assume that the cluster space density is a power-law function of galactocentric radius:

$$\psi(R) \propto R^{-\alpha}. \quad (16)$$

The concentration parameter α lies within the [2, 3] interval (Sharov 1976; van den Bergh 1988) and is close to $\alpha = 2.7 \pm 0.2$ for well-studied normal galaxies and $\alpha = 2.3 \pm 0.1$ for giant cD-type galaxies (Sharpless 1988; Harris 1991, 1993; Harris *et al.* 1995).

Judging by the part of Galactic globular cluster population that is least affected by evolution $W(M > 10^5 M_\odot, R > 4.5$ kpc) the initial globular cluster population also had a power-law mass distribution (Surdin 1979):

$$f(M) \propto M^{-2}. \quad (17)$$

This result agrees with observations of clusters in other galaxies (Racine 1980; Richtler 1992) and is consistent with the theories of pregalactic origin of globular clusters (Peebles and Dickey 1968; Peebles 1984; Rosenblatt *et al.* 1988). Obviously, the mass distribution must have a low-mass cutoff at a certain limiting cluster mass value, M_t, resulting from a cutoff in the initial globular cluster mass function. M_t is likely to lie within the $(10^3$–$10^4)M_\odot$ interval. However, the limiting observed mass values, M_{lim}, in the star cluster counts in external galaxies usually fail to reach M_t. Therefore, in the general case when calculating N we distinguish between the above two quantities and assume that the lower mass in the integration is equal to $M_m = \max\{M_{lim}, M_t\}$. The intersection of $M_d(R, t)$ and $M_f(R, t)$ lines with M_m on the R–M plane (Fig. 1) yields distance $R_m(t)$:

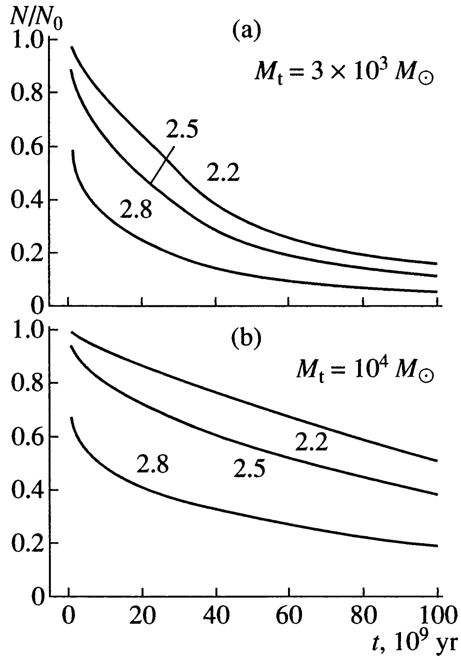

Fig. 2. The relative number of globular clusters in a galaxy of radius $R_g = 30$ kpc and circular velocity $V_c = 200$ km s^{-1} as a function of time. The minimum cluster masses ($M_m = M_t$) are shown. Concentration parameter, α, are indicated near each curve.

$$R_m = \begin{cases} 1.3\left(\dfrac{V_c}{100 \text{ km s}^{-1}}\right)\left(\dfrac{t}{10^{10} \text{ yr}}\right)\left(\dfrac{M_m}{10^4 M_\odot}\right)^{-1} \text{kpc}; \\ M_m < M_s, \\ 1.6\left(\dfrac{V_c}{100 \text{ km s}^{-1}}\right)^{-1/2}\left(\dfrac{t}{10^{10} \text{ yr}}\right)^{1/2}\left(\dfrac{M_m}{10^6 M_\odot}\right)^{1/2} \text{kpc}; \\ M_m > M_s. \end{cases} \quad (18)$$

The order of integration in formula (14) should be reversed when R_m reaches R_s or R_g.

We now designate $\beta = 3 - \alpha$, $\gamma = 4 - \alpha$, and $\delta = \alpha - 1$ and find from (13) and (14) the relative number of clusters:

$$\frac{N}{N_0} = \frac{M_t}{M_m}\left[1 - \left(\frac{R_m}{R_g}\right)^\beta - \frac{\beta}{\delta}\left(\frac{R_m}{R_g}\right)^\beta + \frac{\beta}{\delta}\left(\frac{R_m}{R_g}\right)^{2-}\right]; \quad (19)$$

for $M_m \geq M_s$;

$$\frac{N}{N_0} = \frac{M_t}{M_m}\left[1 - \frac{1}{\gamma}\left(\frac{R_m}{R_g}\right)^\beta - \frac{3\beta R_s}{\gamma\delta R_m}\left(\frac{R_s}{R_g}\right)^\beta + \frac{\beta R_s}{\delta R_m}\left(\frac{R_s}{R_g}\right)^{2-}\right]; \quad (20)$$

for $M_s > M_m$ and $R_m > R_g$.

Obviously,

$$\frac{N}{N_0} = \frac{M_t}{M_s}\left[\frac{\beta R_g}{\gamma R_s} - \frac{3\beta}{\gamma\delta}\left(\frac{R_s}{R_g}\right)^{\beta} + \frac{\beta}{\delta}\left(\frac{R_s}{R_g}\right)^2\right]; \quad (21)$$

for $M_{\rm lim} > M_f(R_g)$, $N/N_0 = 0$.

To illustrate the resulting relation, we computed the evolution of the relative number of clusters in model galaxies (Fig. 2) assuming that all clusters that have survived until the present epoch had been discovered ($M_m = M_t$). The fraction of such clusters can be seen to depend strongly on the concentration parameter α and the lower limit M_t of the cluster mass function.

Only less than half of all initial globular clusters could have survived until the present-day epoch ($t \approx 1.6 \times 10^{10}$ yr) in a typical galaxy, this fraction being higher in galaxies with the lowest α. As we will see below low α values are a typical feature of cD-type galaxies.

SPECIFIC FREQUENCY OF GLOBULAR CLUSTERS IN DIFFERENT GALAXIES

The specific frequency of globular clusters per unit luminosity of the parent galaxy is defined as $S_N = N_t \times 10^{0.4(M_V^T + 15)}$, where N_t is the total number of clusters and M_V^T, the absolute magnitude of the parent galaxy in the V filter (Harris and Racine 1979). N_t is usually calculated from the observed number of clusters, N, assuming Gaussian form of the initial mass function (IMF). The choice of the IMF is very important because the above procedure sometimes yields $N_t/N \sim 10^2$ (Harris 1991). As noted above, in the domain only slightly affected by evolution the IMF of globular cluster populations in well-studied galaxies has a power-law and not a Gaussian form. Therefore we consider the generally adopted definition of S_N unsatisfactory.

The interpretation of this quantity also provokes objections: it is believed that theories of pregalactic globular cluster formation imply the same S_N for all galaxies for the present-day epoch. However, N_t would be expected to be proportional to the mass and not to the luminosity of the galaxy (and it is not yet clear to what mass–baryonic or total mass which includes the missing mass) and during the formation and not during the present-day epoch.

The traditionally determined S_N values are equal to 1–3 for spiral galaxies; 2–10 for ellipticals (S_N increases with the richness of the host cluster), and $S_N \approx$ 10–15 for giant cD-type ellipticals (Harris 1991). Such a wide range of S_N stimulates far-reaching cosmogonic conclusions concerning not only star clusters but also entire galaxies. However, we have already showed that dynamical evolution causes S_N to depend on time in varying degrees in different galaxies depending on the structure of the globular cluster system (parametrized by α). Obviously, even if the clusters initially form in proportionate numbers to the mass of the parent galaxy and all galaxies have the same initial cluster distribution in space, the present-day S_N must be a function of the mass of the galaxy.

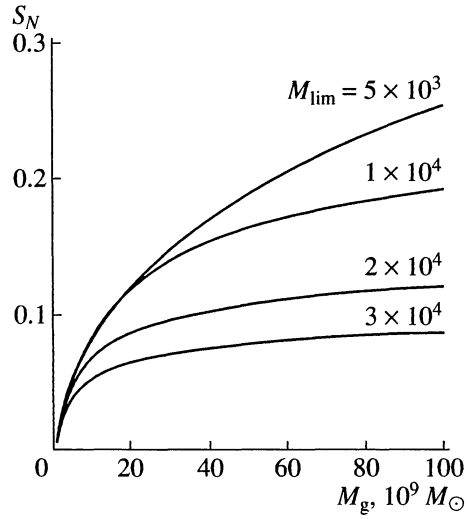

Fig. 3. The observed specific frequency of globular clusters scaled to the unit mass of the galaxy as a function of the mass of the galaxy. S_N is given for $t = 1.6 \times 10^{10}$ and scaled to S_N value for $t = 0$. We adopted $\alpha = 2.7$ and $M_t = 5 \times 10^3 M_\odot$. The observed limiting mass, $M_{\rm lim}$, in solar units is indicated near each curve.

To analyze variation of S_N along the galactic mass and morphological type sequences, we use the combined Faber-Jackson and Tully-Fisher relation linking the circular velocity and luminosity, $L \propto V_c^4$ (de Zeeuw and Franx 1991). To convert luminosities into masses, we must adopt a certain M/L ratio, which for normal Sc to E galaxies is virtually independent of morphological type and depends only slightly on the mass/luminosity of the galaxy (Sersic 1982). We therefore use the data for elliptical galaxies of different masses, which are of greatest interest to us because their globular cluster systems are more uniformly investigated. Note, however, that our results can be applied virtually to all galaxies except the dwarf ones.

In the (1.5–20) × $10^{11} M_\odot$ mass interval the mass-luminosity ratio for elliptical galaxies is $M/L_B = 9.5 \pm 3.2$ (Bertin *et al.* 1988) and is virtually independent of mass. In a wider mass range (from 10^9 to $10^{12} M_\odot$) $5 < (M/L_B) < 12$ with a slight increase toward massive systems (Binney 1982). Formula $M/L_B = 9(L_B/10^{10} L_\odot)^{1/8}$ can be therefore considered sufficiently accurate for our computations. This formula yields, in view of the Faber-Jackson relation, the following normalized relations:

$$V_c = 210\left(\frac{M_g}{10^{11} M_\odot}\right)^{2/9} \text{ km s}{-1}, \quad (22)$$

and

$$R_g = 10\left(\frac{M_g}{10^{11}M_\odot}\right)^{5/9} \text{ kpc} \tag{23}$$

for the circular velocity and the radius of the galaxy, respectively.

We now substitute these relations into (19)–(21) and assume the number of globular clusters to be proportional to the mass of parent galaxy ($N_0 = kM_g$) to estimate the present-day value of $S_N(M_g) = N/M_g$ for galaxies of various masses (see Fig. 3).

The above computations lead us to the following two important conclusions:

(1) the fraction of survived clusters increases with the mass of the parent galaxy. Therefore all factors being equal we must expect the observed present-day S_N value to increase when passing from Irr and Sc galaxies to E and, especially, cD-type galaxies;

(2) Due to strong evolutionary depletion in nearby low-mass galaxies (LMC- and M33-type galaxies), extremely small number of clusters should be revealed even by the deepest cluster counts.

Recall that these conclusions hold only for galaxies strictly obeying the Faber-Jackson (or Tully-Fisher) relation and completely covered by cluster counts down to a limiting mass of M_{lim}.

CONFRONTING THEORY WITH OBSERVATIONS

On the whole, the conclusions drawn from evolutionary calculations at the end of the previous section are consistent with observations. Thus, the present-day S_N values increase along the sequence of galaxy types: from Irr to E and, especially, to cD (Harris 1991). However, this increase is accompanied by increase in the scatter of individual S_N values, which is mostly due to the difficulty of observing distant massive systems. The observed S_N values cover a range of almost two orders of magnitude.

We used published galaxy and cluster-count data (Harris 1991) to calculate from formulas (19)–(23) the initial populations of globular cluster systems, (N_0), and the initial specific frequencies of clusters scaled to the unit mass of the galaxy, S_{N_0}. We adopted for all clusters the same color index $B–V = 0.7$ and the mass-luminosity ratio $M/L_V = 2$. We also assumed all galaxies to have the color index of $B–V = 0.9$. Figure 4 shows the results for ellipticals and SO galaxies. So far we did not analyze spiral and irregular galaxies because of greater variety of their photometric and dynamical properties.

Note that S_{N_0} is virtually the same for all early-type galaxies and the range of S_{N_0} values reduces to one and a half orders of magnitude compared to the that of S_N

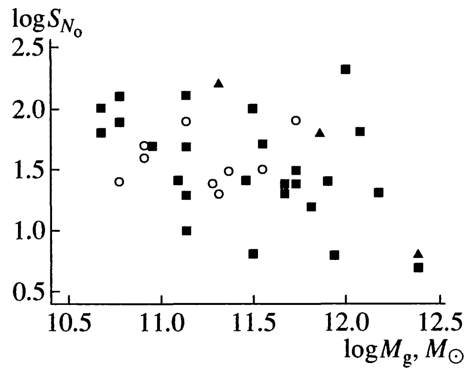

Fig. 4. The calculated specific frequency of globular clusters per unit ($10^9 M_\odot$) mass of the galaxy at the formation epoch ($t = 0$). Squares show E-type galaxies ($\alpha = 2.7$); triangles, cD-type galaxies ($\alpha = 2.3$), and circles, S0 and SB0-type galaxies ($\alpha = 2.7$). We adopted $M_t = 10^4 M_\odot$. Observational data are taken from Harris (1991).

with most of the scatter accounted for by distant massive systems. The S_{N_0} values depend mainly on the adopted M_t, i.e., it they are model-dependent. However, the fact that the order of S_{N_0} values is preserved throughout a rather wide range of masses and galaxy types suggests that this quantity reflects some real properties of the globular cluster system at the time of galaxy formation.

The galaxies shown in Fig. 4 have masses in the range $(0.4–25) \times 10^{11} M_\odot$. Our calculations show that a reconstruction of the initial population of globular cluster systems in these galaxies without allowance for dynamical evolution would underestimate the initial number of clusters by a factor of 1.5–2. However, this effect is more pronounced for low-mass galaxies. Thus, based on its mass, $1.3 \times 10^9 M_\odot$, and the average $S_{N_0} = 35/(10^9 M_\odot)$ for elliptical galaxies (see Fig. 4), we would expect the compact elliptical galaxy M32 to contain about 40 clusters. In view of the limiting magnitude of existing surveys (Harris 1991) at least 10 clusters discovered must have been discovered in this galaxy. However, our allowance for dynamical evolution formally reduces the expected number of clusters to unity. Actually, no clusters have been found in M32 (except for the nucleus of the galaxy). Therefore the absence of globular clusters in such systems can be explained only by accounting for cluster disruption.

CONCLUSION

We calculated the evolution of the number of globular clusters in an arbitrary galaxy taking into account the two most important dynamical effects that reduce the population of these objects, namely, dissipation and dynamical friction. We adopted a number of serious simplifying assumptions: isothermal galaxy model, circular orbits of clusters and the absence of galactic disk induced dynamical effects, e.g., tidal shocks from the disk as a whole and from individual molecular clouds (Spitzer 1987; Surdin 1996; Ashman and Zerf 1992). Therefore our results should be more applicable to elliptical galaxies and we limit our comparison of theory with observations to such systems. Note, however, that according to our preliminary estimates, the results can be applied to disk galaxies as well.

Another important limitation of our model results from the fact that we assume the same cluster mass function ($dN/dM \propto M^{-2}$) for all galaxies. Although in the massive and intermediate-mass cluster range this mass spectrum is consistent with observations, it is not improbable that the form of the mass spectrum can be more complex in the low-mass ($M < 5 \times 10^4 M_\odot$) domain.

When comparing theory with observations we assumed that cluster counts provided complete coverage of the galaxy by cluster counts within R_g. Usually this is not the case: in the central part of the galaxy cluster counts are make difficult because of high surface brightness and in the peripheral regions, because their require too much observing time. Detailed analyses of a number of galaxies, e.g., NGC 5128 (Minniti *et al.* 1996), showed that only a small fraction of clusters (~ 1%) might have been missed in their central parts. However, this effect can be much stronger in the outer regions.

Our computations allowed us to draw the following principal conclusions:

(1) The fraction of currently survived clusters in a galaxy increases with the mass of the latter. This is consistent with the observed increase of the specific frequency of globular clusters (S_N) when passing from late-type (Irr and Sc) to early-type galaxies (E and S0).

(2) In typical large galaxies, no more than half of the original globular clusters could have survived until the present-day epoch and in low-mass galaxies, only several per cent. It is this effect that explains, e.g., the absence of globular clusters in the compact elliptical galaxy M32.

(3) The fraction of clusters survived depends on the spatial distribution of clusters within the galaxy. We assumed the cluster density distribution in the form $\psi(R) \propto R^{-\alpha}$ and found that the fraction of clusters survived in the galaxy increases with α. This agrees with relatively more numerous globular cluster populations in giant cD-type ellipticals, which have the highest α values.

(4) Our attempt to reconstruct the number of original globular clusters showed the specific (per unit mass of the galaxy) frequency of clusters, S_{N_0}, to be virtually independent of the mass of the galaxy. We cannot consider it a final result because of the limited range of galaxy types involved (S0–E–cD) and the use of averaged Faber-Jackson-type relations instead of detailed models of individual galaxies. However, if confirmed by more detailed analyses of globular cluster systems in galaxies of different types, the conclusion that all systems have the same S_{N_0} would be of greatest importance for the problem of globular cluster origin and evolution of galaxies.

In the future, we plan to construct detailed evolutionary scenarios for the systems of globular clusters and dwarf spheroidal galaxies in nearby and well-studied galaxies based on individual dynamical models. The application of the results of these computations to distant galaxies will allow more justified statistical analysis of the systems of globular clusters and dwarf spheroidal galaxies and more reliable conclusions about the origin of these systems.

Of special and great interest is the investigation of globular clusters in satellite galaxies. Thus, Fornax dwarf galaxy, which is much less massive than M32, contains several globular clusters. Therefore the evolution of globular cluster systems is not determined entirely by the mass of the parent galaxy: a second parameter is needed, e.g., the radius of the galaxy, although detailed dynamical model would be preferred. This is the only way to understand genetical association between globular clusters, dwarf and massive galaxies. And there remain less and less doubts that such association exists (Ashman and Zerf 1992; Larson 1996).

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